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ORIGINAL PAPER

Dams or ponds classification based on a new criterion to assess potential flood damage to roads in case of failure

Eduardo Martínez-Gomariz[1,2,3] · Carlos Barbero[4] · Martí Sanchez-Juny[3] · Edwar Forero-Ortiz[1,2,3] · Marcos Sanz-Ramos[3]

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Abstract
Dams are hydraulic infrastructure that have several purposes, such as irrigation, hydropower, water supply, flood control, recreation, fish breeding and navigation. However, their failure or malfunctioning can pose a threat to downstream communities, and thus, their safety is paramount to public protection and economic security. A variety of approaches to classify dams can be found in countries worldwide. Their classification allows to distinguish among those that are to be subject to safety regulation in each country. A common approach to classify them is according to their potential damage in case of failure. Roads are usually among the infrastructures that these approaches consider to be assessed in terms of the level of damage that can suffer. A new people-centred criterion is proposed in this paper to assess potential intangible damage (i.e. human lives) when roadways could be flooded due to a dam failure. This novel methodology is based on the Average Daily Traffic (ADT) of roadways and sets a maximum and a minimum number of vehicles expected in the area receiving the flood. To evaluate its appropriateness, it is verified from the results obtained after being applied to three existing ponds located in Catalonia (Spain).

Keywords Dams · Safety · Potential damage · Roadways · Vehicles' stability

1 Introduction

Dams are essential and multipurpose hydraulic structures. Irrigation, hydropower, water supply, flood control, recreation, fish breeding and navigation are the primary purposes of constructing dams. Often, although one main goal prompted its construction, different uses

✉ Eduardo Martínez-Gomariz
eduardo.martinez-gomariz@upc.edu

1 Department of Critical Infrastructure Management and Resilience, Cetaqua, Water Technology Centre, Cornellà de Llobregat, Barcelona, Spain

2 Innovation and Knowledge Department, Aigües de Barcelona, Barcelona, Spain

3 Flumen Research Institute, Universitat Politècnica de Catalunya - Centre Internacional de Mètodes Numèrics en Enginyeria, Barcelona, Spain

4 Department of Infrastructures for Water Control and Regulation, Agència Catalana de l'Aigua (ACA), Barcelona, Spain

are given to the same dam. The world's dams, being thousands of them built during the last 100 years, are ageing, resulting in deterioration, and becoming a severe threat to the downstream settlements. If corrective measures seem to be impractical or very costly, then the question of decommissioning them should be addressed seriously (Adamo et al. 2020).

Dam failures are low-probability and sudden events which often have significant consequences. There are several reasons for a dam failure: (i) overtopping, (ii) structural failure, (iii) movement of the foundation, (iv) cracking, (v) internal erosion, (vi) inadequate maintenance, and vii) sabotage. The sudden and uncontrolled release of water due to a dam failure can cause highly adverse impacts such as a massive loss of human lives. Any dam or water-retaining structure, no matter how small, represents a potential danger to downstream life and property.

Dam safety is paramount to public protection and economic security. A central element of any regulatory regime is establishing objective criteria for determining those dams that are to be subject to regulation. The selection of appropriate safety requirements for the various categories of dams is often based on their classification, adopted with different formulations in several countries (ICOLD European Club 2012). The appropriate thresholds for these classifications should consider the local context, and the regulatory regime must capture hazardous dams. Dams' size, type, reservoir volume, *potential damage in case of failure*, and a combination of them are the aspects usually considered in the classification systems in all countries. Wishart et al. (2020) conducted a comprehensive survey of 51 countries regarding their regulatory framework for dams safety, covering 70 per cent of the world's total land area and 80 per cent of the world's population. A similar survey was conducted by the International Commission on Large Dams (ICOLD) European Club (ICOLD European Club 2012) to analyse the situation of 9 European Countries in terms of safety of existing dams. From both studies, it is clear that dam safety harmonisation is difficult for all countries in many aspects. Twenty-seven per cent of the case studies considered by Wishart et al. (2020) have a combined classification scheme, and 22 per cent relied on a classification based on the potential damage in case of failure.

The classification system by potential damages varies by country. While some consider a descriptive potential damage (e.g. Canada and Sweden), others propose more specific damage classification systems by providing threshold values for different categories, such as the number of people at risk or potential loss of life (e.g. Australia, Indonesia, South Africa, Spain, and Washington State in the United States). However, not only loss of life is considered as an aspect of this potential damage-based classification, but additional losses that can occur as a result of dam failure are frequently proposed (e.g. public health, property, transport infrastructure and environmental resources).

Guidelines are provided in some countries (U.S. Department of the Interior 1988; Federal Emergency Management Agency (FEMA) 2004, 2012; Dominitz 2013; Government of Tasmania 2015; Government of India 2020) to outline the procedures for identifying and assessing the potential damages of dam failure (Fig. 1). Usually, it is the dam owner who, according to these guidelines, develop a report to propose a classification of their dams based on the potential damage assessment. This report must be submitted to the corresponding public authority to be evaluated and, if the evaluation is positive, the dam will be officially classified as proposed.

In general, to estimate the potential damage in the case of a dam failure, the human lives, the property, and the environmental values that could be affected by the flood caused need to be evaluated. Roads and highways are among the different elements and infrastructures that could be affected by the flood caused by a dam failure. These guidelines mainly refer to them as potential physical damage due to exposure to the flood. However, with

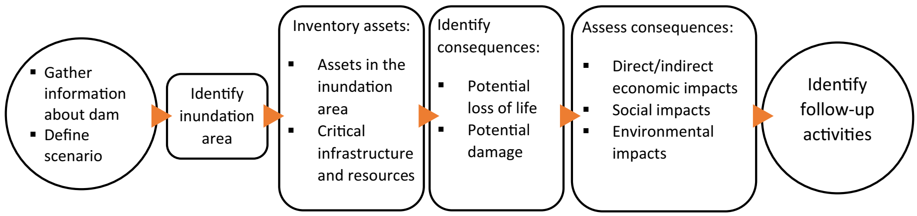


Fig. 1 Potential damage assessment process (Federal Emergency Management Agency (FEMA) 2012)

greater or lesser likelihood, vehicles directly, and thus persons indirectly, can be exposed to the flood depending mainly on the road's vehicular intensity. Therefore, the level of damage must be established according to the expected number of people at risk.

This paper presents a new criterion to assess potential intangible damage (i.e. human lives) when roads are exposed to flooding due to dams or ponds failure in a context of dams' safety guidelines. This is a population-oriented approach (i.e. occupation of vehicles in circulation), unlike the current damage assessment criteria based exclusively on physical damage to roads. The following section will pay attention to the terminology used in this article. Following, the methodology section is presented with three subsections: (i) an overview of the Spanish dam safety regulation in terms of dams' regulation and the specific case of Catalonia, (ii) the current methodology to classify dams according to their potential damage in case of failure, and iii) the population-oriented new method to assess damage to potentially flooded roadways. Section four addresses the application of this methodology to three ponds in Catalonia, where a comparison of the ponds' classification will be carried out under both current and new approaches. The fifth section will provide a discussion of results, and the sixth section will present the conclusions of this study.

2 Risk and potential damage concepts

The concept of risk is used in different fields, such as dam engineering, disaster risk reduction, and flood risk management. This concept has evolved over time, and today different approaches can be found, some more complex than others and even the term is sometimes misused. Some studies present the different approaches and components of risk (Thywissen 2006), discussing the definitions of each of its features. Shabman and Scodari (2014) define flood risk as "the probability and adverse consequences of floods". The risk of flooding of goods and people is a function of the hazard in this location and its exposure and vulnerability to the flood hazard. On the other hand, they define flood damage as the adverse consequences for people and property expected of their exposure and vulnerability to the flood hazard. Flood damage is functionally related to the magnitude and characteristics of a flood conducted and the exposure and vulnerability of elements at risk. In some cases, exposure is considered part of the vulnerability (Turner et al. 2003).

Therefore, unlike the potential damage (or consequences), risk incorporates the probability of flood occurrence (or dam failure). In the present case, what is assessed is the potential damage (or consequences), as the probability of failure of the dam/pond is not considered. This is how it is described in international dam classification guidelines, where the concept of risk is not used but of consequences, potential harm or, less accurately, hazard. Paradoxically, to avoid misinterpretations, the concept of hazard is mostly used to refer to the potential damage downstream of a failed dam (Wishart et al. 2020).

Figure 2 presents the different risk components. The potential damage or consequences are part of the risk concept used here to classify dams and ponds. In our case, flood hazard is mainly linked to the hydraulic variables: flow velocity and depth that impact the element or person at risk. Therefore, levels of hazard (e.g. high, medium, low) can be proposed for these elements and people based on aspects such as their stability or resistance to different combinations of water depths and velocities (Shand et al. 2011b; Russo et al. 2013; Chanson and Brown 2015; Xia et al. 2016; Martínez-Gomariz et al. 2016, 2018; Kramer et al. 2016; Milanesi and Pilotti 2019; Martínez-Gomariz et al. 2020). The output of a hydraulic model of a flood event can be translated into a hazard map once the criterion is defined, relating the hydraulic variables (i.e. depth and velocity) to the proposed hazard levels (Mosquera-Machado and Ahmad 2007; Vasconcellos et al. 2021). In this way, the high-hazard areas (and medium if so decided) will be delimited on the map to analyse the exposed elements and population.

The level or degree of potential damage to an element or person depends primarily on their vulnerability to a particular hazard (flood). However, an element or person can only be subject to a certain level of damage if it is vulnerable to the hazard. The concept of vulnerability presents more definitions in the literature and greater complexity. A complete definition of this is provided by Turner (2003), who considers vulnerability composed of exposure, sensitivity, and resilience (Fig. 2).

In this case, the resilience component will not be regarded as in the study of dam classification no possible adaptation measures can be considered.

According to this definition of potential damage, an element or person without exposure ceases to be vulnerable to a particular hazard and will therefore not present any damage. Sensitivity and resilience will characterise the level or degree of damage by a specific hazard to which an element or person is exposed.

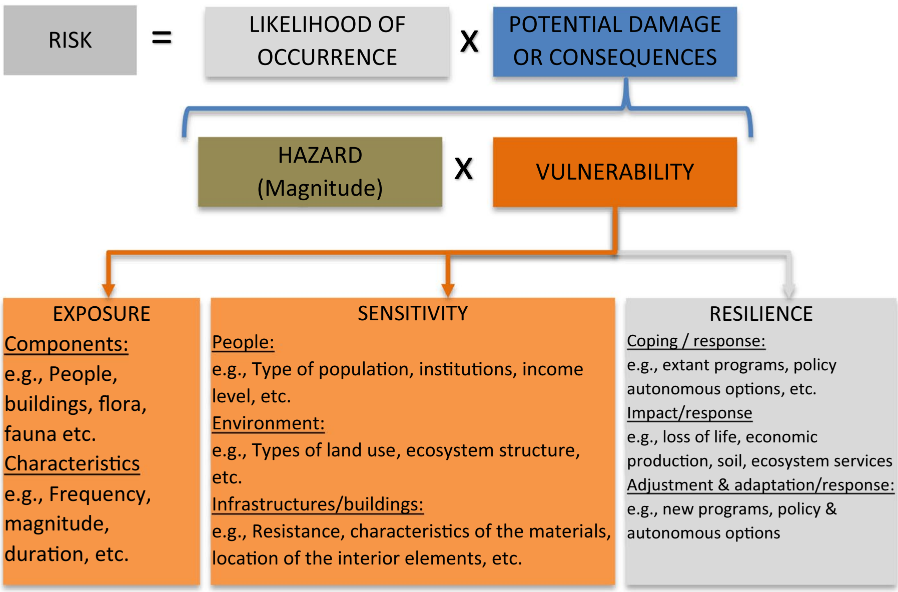


Fig. 2 Components of risk, potential damage, and vulnerability (Turner et al. 2003)

On the other hand, damage can be tangible (e.g. economic) or intangible (e.g. loss of life). At the same time, this damage can be direct or indirect (Martínez-Gomariz et al. 2019). For example, a flooded home will present tangible and direct damage, but a flooded business can also result in significant indirect damage such as loss of turnover during the time back to normal after the flood. The concepts defined in this section will be used in this paper.

3 Materials and methods

3.1 Dams classification in Spain and the Catalan case study

The Spanish classification consists of evaluating the potential damage induced by an eventual dam failure, according to which the dams can be classified into three categories:

- Category A: Corresponds to dams whose failure or improper operation can seriously affect urban areas or essential services or cause significant material or environmental damage.
- Category B: Corresponds to dams whose failure or improper operation can cause significant material or environmental damage or affect a small number of dwellings.
- Category C: Corresponds to dams whose failure or incorrect operation can cause material or environmental damage of moderate importance and only incidentally loss of life. This category will include all the dams not included in Categories A and B.

In order to standardise the Spanish dams classification process, a national Technical Guide (Ministerio de Medio Ambiente de España 1996) was published in 1996 and updated in 2021 (Ministerio para la transición ecológica y el reto demográfico 2021). Practically all state-owned dams and a large part of the privately owned dams have already been classified based on the methodology proposed in this Technical Guide. In 2015, there were a total of 1,623 state-owned dams, of which 743 (46%) are classified as A, 118 (7%) as B, and 762 (47%) as C. This methodology is briefly described in Sect. 3.2.

In Catalonia, the classification will be carried out by resolution of the Catalan Water Agency (ACA for its acronym in Catalan) for the dams located in the public hydraulic domain of the River Basin District of Catalonia and the ponds located outside the public hydraulic domain of the entire Catalan territory, based on the dam or pond classification proposal provided by the owner. For inter-community basins, the classification resolution will be carried out by the "General Water Directorate" of the Spanish "Ministry for the Ecological Transition and the Demographic Challenge". Currently, 80 dams and 101 ponds are classified as A, B or C in Catalonia (Fig. 3).

3.2 The methodology proposed by the Spanish Technical Guide for Dams Classification according to their downstream potential damage

The Spanish Technical Guide (Ministerio de Medio Ambiente de España 1996) indicates that the level of hazard is a function of the hydraulic variables (depth and velocity) of the flood produced by the dam failure. To assess flood hazard, empirical relationships between these two variables are provided. Three zones are defined in the depth-velocity domain (hazard-level criterion): low danger, judgement, and high danger concerning potential

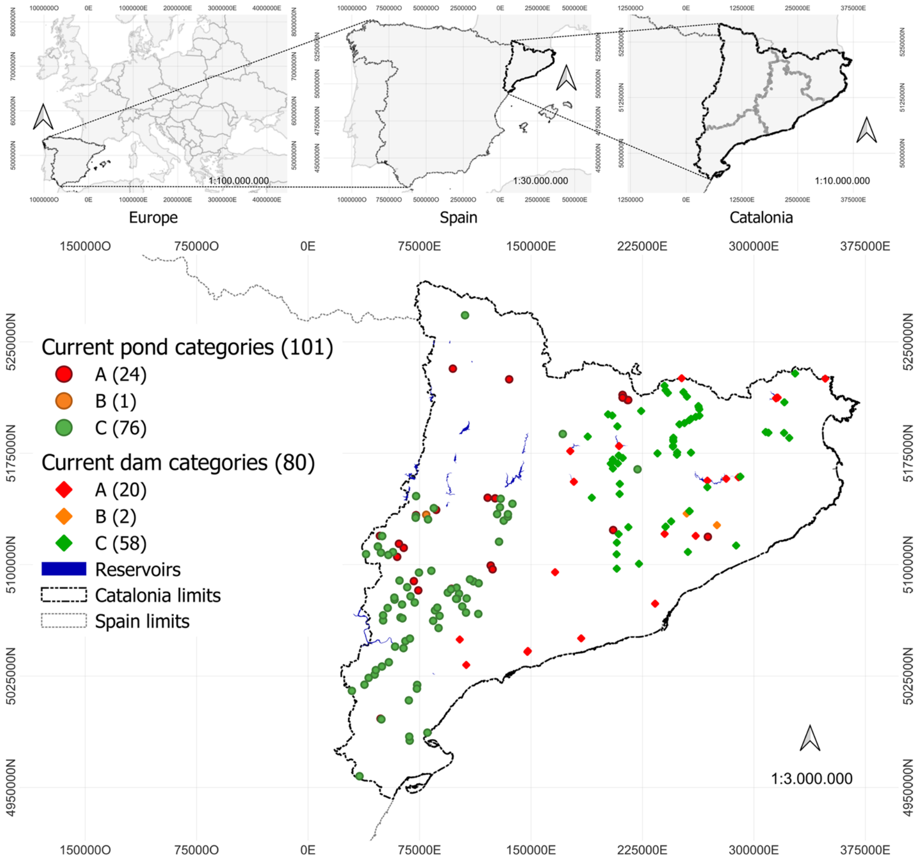


Fig. 3 Catalonia region and its dams and ponds (elaborated from data provided by the ACA)

damage to human lives. These thresholds are defined by the case of flooding over urban areas (Fig. 4a) and by the possibility of flooding over non-urban areas (Fig. 4b). These two hazard criteria correspond exactly to two of the criteria proposed by the U.S. Bureau of Reclamation (USBR) in their "Downstream Hazard Classification Guidelines" (U.S. Department of the Interior 1988) (Fig. 5). The proposal in the Spanish Technical Guide for urban areas (Fig. 4a) coincides with the resistance of the structure for housing on foundations (Fig. 5b) and the non-urban areas (Fig. 4b) with the danger for the stability of adults on pedestrian routes (Fig. 5d). This identification was made by Russo et al. (2014), further discussing the appropriateness of applying these hazard criteria.

In November 2021, this Technical Guide was updated (Ministerio para la transición ecológica y el reto demográfico 2021), proposing changes to the hazard criteria. Judgement zones were removed (Fig. 4c), and the non-urban areas criterion was replaced by the threshold proposed by Témez (1992) (Fig. 4d). This latter threshold is indicated in Article 9.2 of the Regulation of the Hydraulic Public Domain (RDPH for its acronym in Spanish) (Ministerio de Obras Públicas y Urbanismo 2020), which states that severe damage to people and property may be considered when hydraulic conditions during the flood meet one or more of the following criteria: a) the water depth is higher than 1 m, b) the flow velocity is greater than

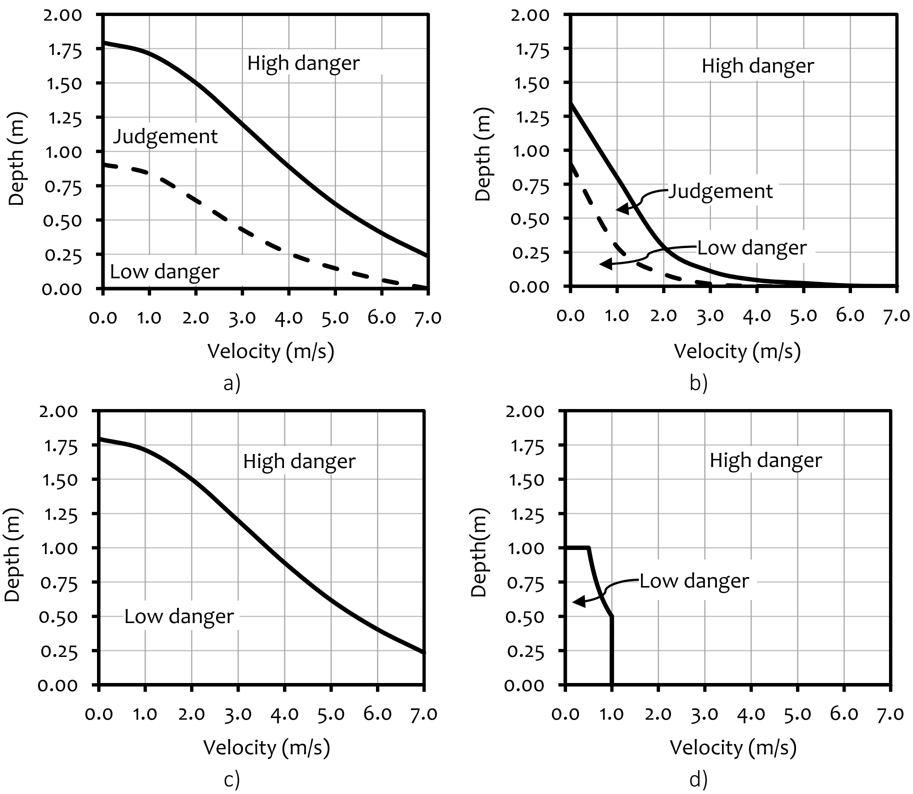


Fig. 4 Danger to human life depending on depth and velocity in the 1996 Technical Guide, a) urban areas and b) non-urban areas, and in the 2021 Technical Guide c) urban areas and d) non-urban areas (adapted from Ministerio de Medio Ambiente de España (1996) and Ministerio para la Transición Ecológica y el Reto Demográfico (2021))

1 m/s, or c) the product of both variables is higher than 0.5 m^2/s. This criterion was based on the works of Bewick (1988) and Jaeggi and Zarn (1990). It is stated to be a conservative one according to the results obtained by Abt et al. (1989).

With these relationships and the results of a hydrodynamic simulation of the flood, hazard maps can be developed where the expected high hazard (high danger in Fig. 4 and Fig. 5) areas could be defined based on both urban and non-urban areas hazard criteria. Crossing this information (hazard) with the elements or people exposed to this hazard (vulnerability), the level of potential damage to people can be defined and classify the dam or pond (i.e. A, B, or C) according to this level (Table 1 and Table 2).

The criterion of potential damage to roadways would be in both Technical Guides only defined by the degree of tangible (economic) damage (significant or very significant) (Table 2) according to the ownership of the roadway.

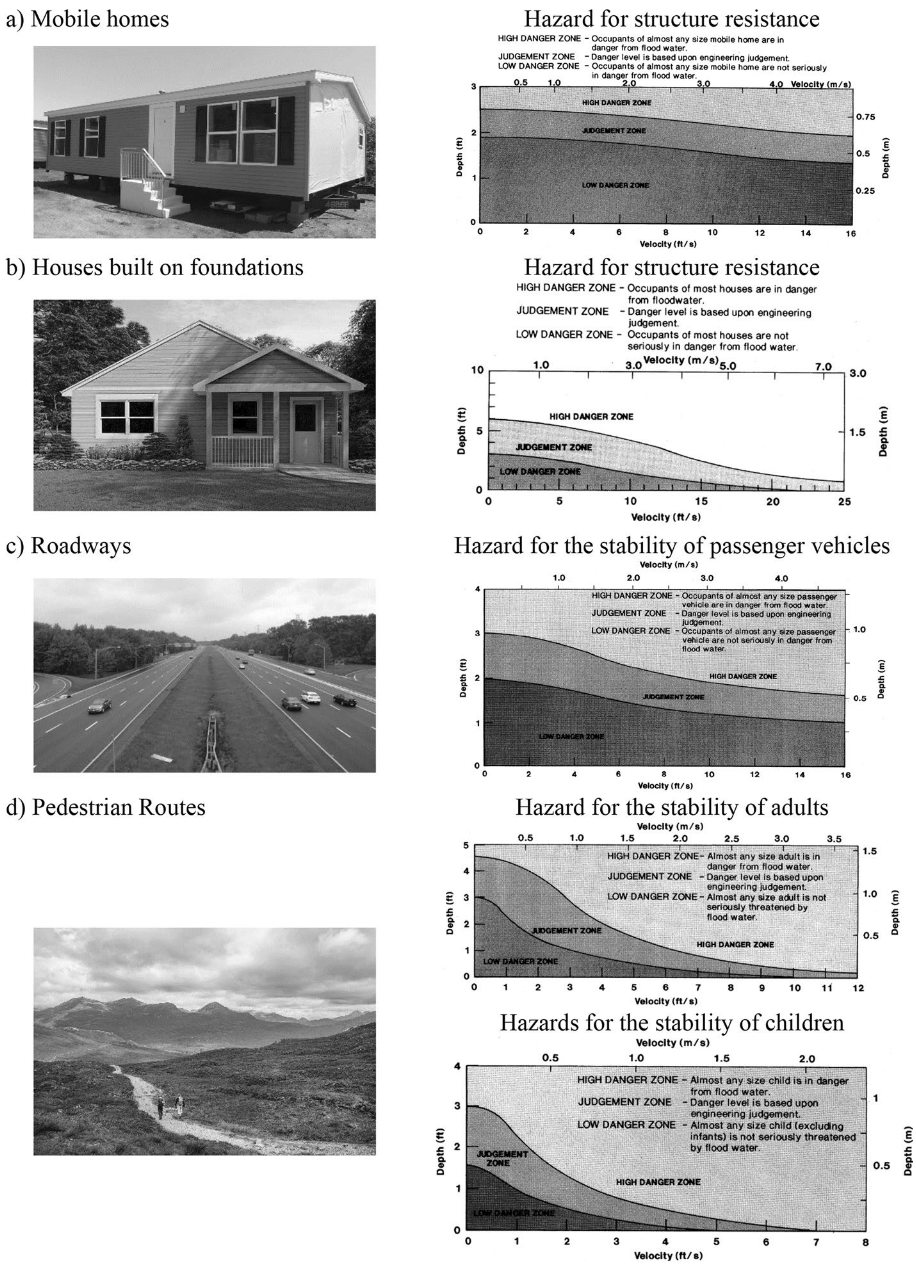


Fig. 5 Hazard criteria proposed by the USBR (Trieste 1990)

3.3 A new methodology to assess potential flood damage to roads in case of dams or ponds failure in Catalonia

In this context of recommendations ("Technical Guide") and regulations (RDPH), there

Table 1 Dam classification according to potential damage levels for human lives (Ministerio de Medio Ambiente de España 1996; Ministerio para la transición ecológica y el reto demográfico 2021)

Type of potential damage	Incidental loss of human lives	Affectation of a small number of homes	Severe impact on urban areas
Human lives (Population at risk)	Occasional and unpredictable presence, over time, of someone on the floodplain	1 ≤ Dwellings ≤ 5	Dwellings > 5
Dam classification	C	B	**A**

is some uncertainty in assessing this potential flood damage when roadways might be exposed. The Catalan Water Agency (ACA) requires clear, easily interpretable, and easy-to-implement criteria. As Wishart et al. (2020) stated, the dam classification system should not be overly complex, as this would put an unreasonable burden on dam owners and/or regulators.

Therefore, in this study, the criteria of hazard and vulnerability will be defined, and the levels of potential damage in case of possible flooding of roads will be proposed, considering human life like central axis.

3.3.1 Hazard criterion

When a road is flooded, the vehicles are directly exposed to the water flow. If hydraulic variables (depth and velocity) do not exceed vehicle stability limits, vehicle occupants will be safe. Therefore, the safety of people will be compromised once the stability of the vehicles is lost.

Different experimental and numerical studies can be found in the scientific literature that analyse the stability of vehicles exposed to water currents (Martínez-Gomariz et al. 2018). A significant number of cars in circulation, frequent floods caused by the growth of urbanised areas, and climate change effects are factors making us see large numbers of vehicles swept away by floodwaters. This recurring situation aggravates the potential damage and risk to pedestrians and occupants of vehicles (Martínez-Gomariz 2016).

In the research conducted by Martínez-Gomariz et al. (2017), 12 types of vehicles on a small scale were tested to determine their stability threshold from curves $(v \cdot y) = a_0$, where a_0 is a constant, different for each type of vehicle. To choose the vehicles, a database of 54 models that can be found on roads was created, along with their corresponding dimensions and weights. These vehicles were ordered according to their potential stability facing a water flow based on the definition of a stability coefficient (SC) (1).

$$\mathrm{SC} = \frac{\mathrm{GC} \cdot M_c}{\mathrm{PA}} \cdot \mu \tag{1}$$

where GC [m] is the ground clearance from the car chassis, M_c [kg] is the mass of the vehicle, PA [m^2] is the area occupied on the floor of the vehicle, and μ [-] is the friction coefficient of the tyres with the ground. The only parameter with uncertainty is the friction coefficient, so a range from 0.25 to 0.75 was proposed according to studies indicating these values for tyres contact with wet pavement (Gerard 2006). In this way, the stability coefficient will have a minimum and a maximum value, thus defining a range of uncertainty.

Table 2 Dam classification according to potential damage levels for infrastructures, crops, and economic activities (adapted from Ministerio de Medio Ambiente de España (1996) and Ministerio para la Transición Ecológica y el Reto Demográfico (2021))

Type of potential damage	Moderate	Significant	Very significant
Damage to industries and industrial estates	Number of installations < 10	10 < Number of installations < 50	Number of installations > 50
Damage to rustic properties			
Damage to rainfed crops	Area < 3,000 Ha	3,000 Ha < Area < 10,000 Ha	Area > 10,000 Ha
Damage to irrigated crops	Area < 1,000 Ha	1,000 Ha < Area < 5,000 Ha	Area > 5,000 Ha
Damage to roadways	Any other lower road category	Regional network of roadways defined by the Department of Territory and Sustainability of the Generalitat de Catalunya (TES)*	Basic Network defined by the TES as well as the state-owned roadway infrastructures*
Damage to railways	–	Narrow-gauge railway	Wide and high-speed railways
Dam classification	C	B	A

*Guide's description has been adapted for the Catalonia region

On the other hand, the experimental stability functions ($(v \cdot y) = a_0$) of the different small-scale models were correlated with the respective stability coefficients of each model tested, obtaining a linear correlation (2). With this expression, the estimation of the stability threshold of any vehicle is possible by calculating only its stability coefficient (SC) (Martínez-Gomariz et al. 2017).

$$(v \cdot y) = 0.01583 \cdot \mathrm{SC} + 0.31985 \tag{2}$$

By calculating the stability coefficients for the 54 vehicles in the database mentioned above, the maximum (with μ_{max}) and minimum (with μ_{min}) stability thresholds for each model were obtained (Fig. 6). This methodology proposes to consider the lower threshold ($(v \cdot y)_{min}$) to stay on the safety side. On the other hand, when water flow velocities are low, the vehicle's instability mode is basically flotation. In this sense, Martínez-Gomariz et al. (2017) proposed an analytical expression (3), validated with experimental buoyancy tests, to obtain the critical depth (h_b) for the vehicle to float.

$$h_b = \frac{M_c}{\rho_w \cdot PA} + GC \tag{3}$$

where ρ_w [kg/m^3] is the density of water. According to the different stability thresholds indicated, it is observed that a value of $(v \cdot y) = 0.4$ m^2/s would guarantee the stability of almost all vehicles. This threshold would correspond to a Seat Ibiza model car, as shown in Table 3 and Fig. 7. Therefore, the proposed threshold would ensure stability for more stable vehicles than a Seat Ibiza model. It should be noted that the values obtained are for unloaded vehicles, and therefore, in reality, it is expected that the weight of their occupation and luggage will provide more stability.

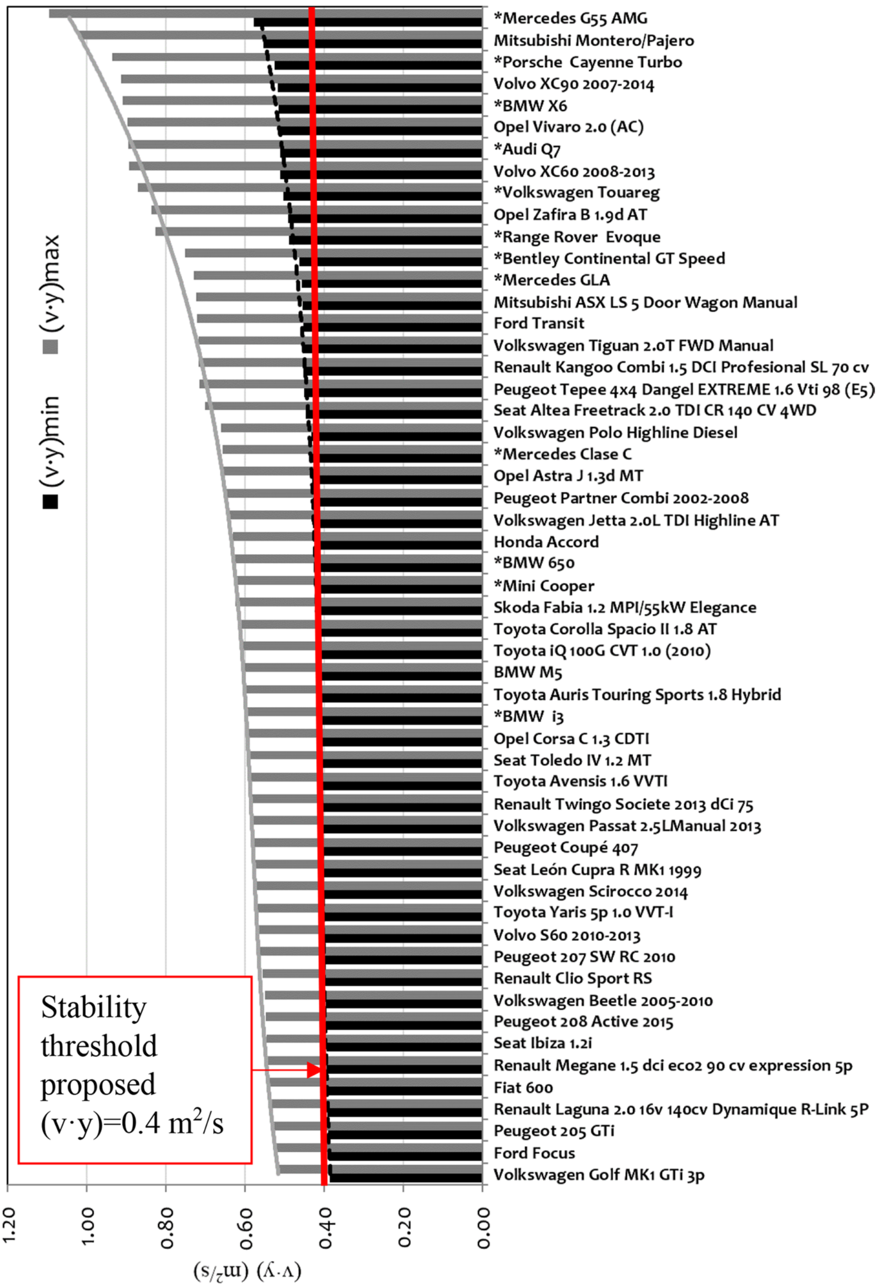
Figure 8 shows this function, along with the limits for passenger vehicles proposed in the USBR (U.S. Department of the Interior 1988; Trieste 1990) (Fig. 5c).

It is observed that the most restrictive criterion in terms of depth is the one proposed here by the Seat Ibiza model ($y = 0.28$ m). The upper limit of the low-danger zone defined by the USBR is much less restrictive than the buoyancy of a Seat Ibiza. It should be noted that the buoyancy rate has been determined according to an analytical formulation (3), which considers two assumptions: (1) the vehicle is watertight and (2) the weight of the vehicle considered is without occupants or luggage (i.e. kerb weight). However, vehicles have occupants, and a certain amount of water is expected to enter them, increasing their weight and thus their stability.

Although the stability threshold for the Seat Ibiza model may seem very restrictive, the internationally recognised Australian Rainfall and Runoff Guide (Shand et al. 2011a) sets a maximum depth of 30 cm for small vehicles. This is a floating depth like the 28 cm obtained here for a Seat Ibiza. Therefore, depths below 28 cm and the stability function of the Seat Ibiza model are proposed as a low-hazard zone. The medium hazard would be in the area between the upper limit of the low-danger zone proposed by the USBR and the stability function of a Seat Ibiza. All combinations of depths and velocities outside these zones would result in high hazard (Fig. 8).

3.3.2 Vulnerability criterion

Vulnerability assessment means answering what will happen if a particular hazard (e.g. flood) impacts the element(s) and/or people at risk. The complexity of assessing vulnerability is such that some authors state that it can only be measured indirectly and



*Tested models

Fig. 6 Stability functions (v·y) = a_0 for different vehicle models (Martínez-Gomariz 2016)

Table 3 Stability threshold and characteristics of a Seat Ibiza model

Model	length (m)	width (m)	floor area PA (m^2)	kerb weight (kg)	GC (mm)	$(SC)_{min}$ (kg/m)	h_b (m)	$(v{\cdot}y)_{min}$ (m^2/s)
Seat Ibiza	4.23	1.69	7.15	1110	124	4.81	0.28	0.40

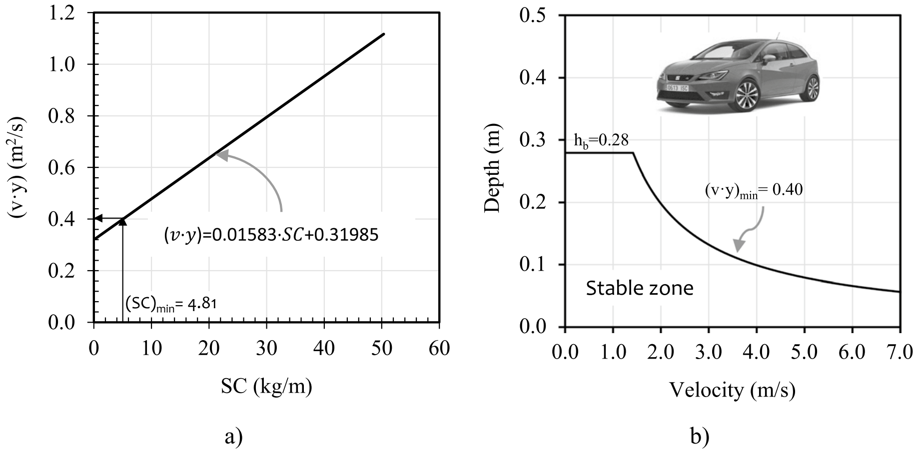


Fig. 7 Stability threshold for a Seat Ibiza model: **a** obtaining its stability threshold from the SC and **b** stability function

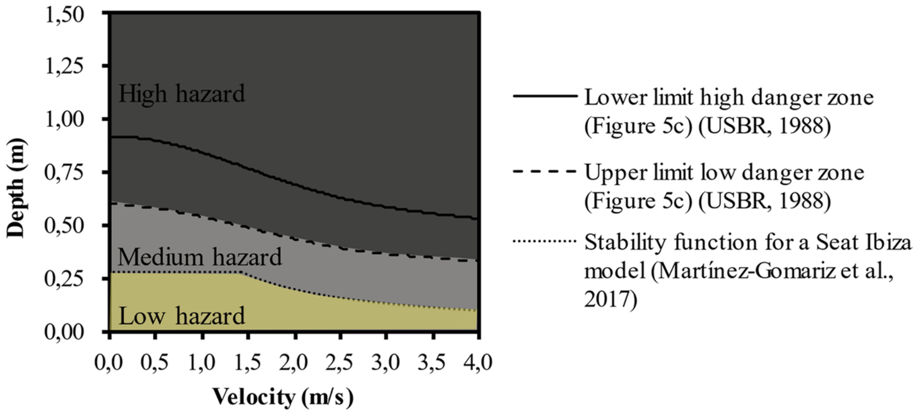


Fig. 8 Hazard criterion proposed

retrospectively, that is, after the disaster. What truly reflects the vulnerability of the affected elements, individuals, or communities is the relationship between the magnitude of the event and the damage caused (Thywissen 2006).

As discussed in the definition of risk and potential damage, vulnerability is the most uncertain component, and there is no consensus on its definition. All the definitions and approaches found in the literature show that we face a paradox as we seek to measure vulnerability when we cannot yet clearly define it. What does seem to be a consensus is that each vulnerability analysis requires adaptation to specific objectives and scales of work. This study will not be an exception, as it presents the particularity of people exposed to floods inside vehicles, which adds a further degree of complexity to measure vulnerability.

In any case, non-exposure of elements and people would not result in risk or potential damage (Fig. 2). Exposure describes the presence of population, environmental services, infrastructure, or other valuable elements in places that may be adversely affected. In the case at hand (i.e. roadways), exposure will be understood as the number of vehicles that may be affected by a flood (Thywissen 2006). Indirectly, vehicle occupants will also be exposed to potential damage.

On the other hand, the sensitivity of people and/or elements exposed to a certain hazard characterise the predisposition that they must suffer damage. In general terms, the dimensions that describe sensitivity are different: physical, social, environmental, cultural, and institutional. In the case at hand, it will be the physical dimension that must be considered concerning vehicles, as aspects such as their age can contribute to the degree of accidents, increasing or decreasing the potential damage to their occupants. Vehicles over 15 years old have been found to have mortality rates up to four times higher than current passenger cars (Real Automóvil Club de España (RACE) 2015).

3.3.2.1 Exposure Compared to dwellings exposed to flooding, vehicles are moving elements and present a higher uncertainty regarding their exposure. To define the expected average vehicle occupancy, the use of vehicle counting data obtained by the public institutions responsible for the roads analysed is proposed. In particular, it will be the Average Daily Traffic (ADT) in each of the measured road sections. Hereinafter, we will refer to this as the ADT criterion.

In Catalonia, the roads affected may be owned by governments of different scales (local, regional, national). Some sources for obtaining this information are presented in Table 4.

Table 4 Sources for obtaining the ADT from roads in Catalonia

Ownership of the Network	Source for the ADT
Road network (primary and regional), defined by the Department of Territory and Sustainability of the Generalitat de Catalunya (TES)	Roads' capacity plan of the Department of Territory and Sustainability of the Generalitat de Catalunya Link April 24, 2021: https://territori.gencat.cat/ca/01_departament/documentacio/mobilitat/carreteres/pla-aforaments/
State-owned road infrastructures	Roads' capacity data provided by the "Ministry of Transport, Mobility and Urban Agenda" Link April 24, 2021: https://www.mitma.gob.es/carreteras/trafico-velocidades-y-accidentes-mapa-estimacion-y-evolucion/datos-mensuales-de-trafico/datos-mensuales-de-trafico-en-la-rce

According to the ADT criterion, the expected number of vehicles per kilometre can be calculated by the expression (4).

$$n_{\text{vehicles}} = \frac{\text{ADT}}{24} \cdot t_{1-2} \tag{4}$$

where $t_{1\text{-}2}$ is the time (in hours) it will take for a vehicle to travel one kilometre at a constant speed. While this vehicle is travelling this kilometre, other vehicles will pass the gauging station at the average time rate indicated by the ADT (ADT/24), contributing to the expected number of vehicles within one kilometre. Since time can be expressed as the distance travelled (1 km) between the speed (v = constant) of the vehicle, the expression (4) can be reformulated, obtaining the expression (5).

$$n_{\text{vehicles}} = \frac{\text{ADT}}{24 \cdot v} \tag{5}$$

where v is the speed limit of the study road. With this assumption, all vehicles circulate at the same speed, and some vehicles are given for the total number of lanes of the flooded road section. Figure 9 graphically represents the relationship between the ADT and the expected number of vehicles per km for different speeds. This is a linear relationship, where $t_{1\text{-}2}$ is the function's slope. The higher the speed, the less time it takes to travel a km.

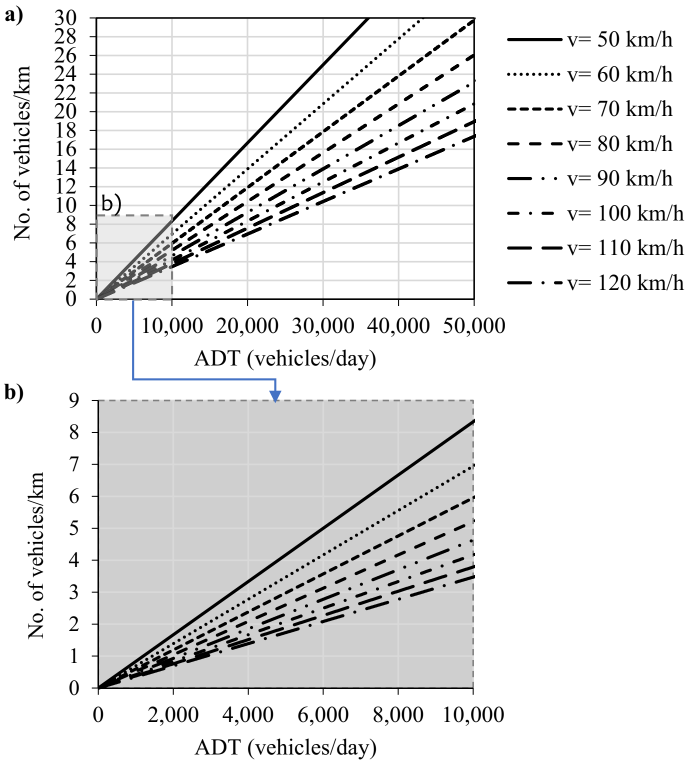


Fig. 9 Estimation of the number of vehicles per kilometre, according to the ADT of the flooded road section, potentially exposed to a flood

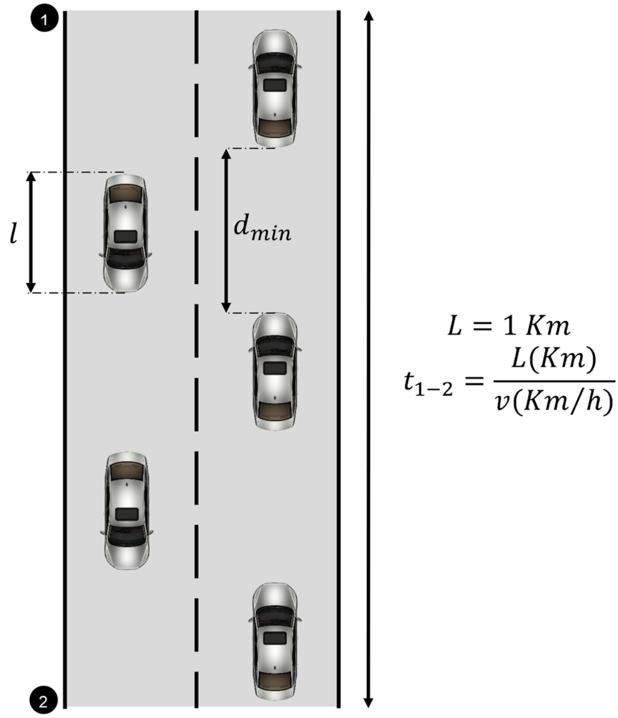


Fig. 10 Distances and time taken to estimate the number of vehicles exposed to a potential flood

Figure 10 illustrates the situation and parameters described for one kilometre of road.

However, it is proposed to define a maximum and minimum number of vehicles that could travel on a road section, so that the number of vehicles obtained by the ADT criterion would be between two thresholds. The maximum expected threshold can be set according to the speed of the road and the safety recommendations regarding the minimum spacing between vehicles. This spacing is usually determined by the driver reaction time.

This time is not defined quantitatively in the Spanish general traffic regulations (Ministerio de la Presidencia 2003), which state that the distance must be sufficient to be able to perform sudden braking in case of need without collision. However, in the case of tunnel traffic, the minimum safety distance is 100 m or four seconds of response time. However, the Roads Instruction (Norma 3.1-IC) (Ministerio de Transportes Movilidad y Agenda Urbana. DG de Carreteras 2020) urges the use of a "perception and reaction" time of 2 s when making calculations of the stopping distance (Sect. 3.2.1 of the 3.1-IC standard). In other countries, there is a two-second rule for passenger cars and a three-second rule for heavy vehicles (Zemanek 2017). It is proposed here, a reaction time of two seconds. Therefore, the safety distance ($d_{\min}$) is defined according to the expression (6), depending on the traffic speed (v).

$$d_{\min} = \frac{2s}{3600s} \cdot v(\mathrm{km/h}) \tag{6}$$

Considering an average vehicle length (l) of 4.3 m, obtained from the database that gave rise to Fig. 6, it is possible to estimate the maximum expected number of vehicles per kilometre of road and per lane (n_{vehicles}) according to a safety distance criterion.

$$\left(n_{\text{vehicles}}\right)_{\max} = \frac{1000}{\left(l + d_{\min}\right)} \tag{7}$$

Table 5 shows the maximum number of vehicles expected for different speeds.

Therefore, the number of vehicles per kilometre to be considered will be obtained according to the ADT criterion using the graph in Fig. 9 or expression (5), without exceeding the maximum threshold established by the criterion of minimum safety distance between vehicles according to Table 5. For example, if it is a two-lane road with a speed limit of 80 km/h with an ADT of 10,000 vehicles/day, the maximum number of vehicles will be 42, but the ADT criterion would determine the number of 6 (5.2 rounded up) vehicles, well below the maximum threshold. Only in some exceptional cases will the safety distance criterion be limiting.

However, situations like the one shown in Fig. 11 may occur, and the ADT criterion may be overly stringent. There are situations in which there is an exit between two traffic counting stations which most of the traffic takes, so after this exit, the number of vehicles can be meagre. As indicated in the Technical Guide (1996 and 2021), the particularities of each situation must be considered to make a realistic analysis.

The Government of Tasmania (Australia), in its technical guide to the classification of dams (Government of Tasmania 2015), proposes that for low-volume roads, aerial images could be used to count the number of vehicles in the road in the vicinity of the river at the time the photo was taken. Alternatively, it offers the opportunity to visit the area that could be affected by the flood and count the number of vehicles that pass for two hours.

It is proposed here as a first alternative, that cases such as the one indicated previously, the vehicles can be counted from aerial photographs from two sources:

(1) The Cartographic and Geological Institute of Catalonia (https://www.icgc.cat/en/Downloads/Aerial-and-satellite-images), and
(2) Google Maps (https://www.google.com/maps).

The number of vehicles within the area occupied by the flood (regardless of their level of hazard, Fig. 8) will be counted, as well as those that appear one kilometre before and

Table 5 Maximum expected number of vehicles according to traffic speed

v (km/h)	Maximum expected vehicle occupancy per kilometre of roadway (No. vehicles/km)*				
	Number of lanes				
	1	2	3	4	5
50	32	64	96	128	160
60	27	54	81	108	135
70	24	48	72	96	120
80	21	42	63	84	105
90	19	38	57	76	95
100	17	34	51	68	85
110	16	32	48	64	80
120	15	30	45	60	75

* Rounded up to get integer numbers

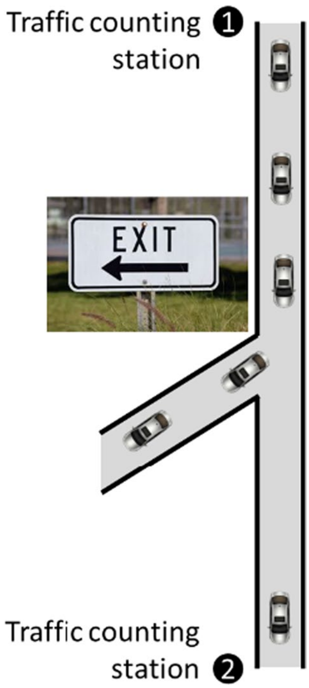


Fig. 11 Exceptional situations where the ADT criterion should not be applied

after. The number of vehicles on display will be considered the largest of those obtained with each image. As a second alternative, in the case of a significant disparity in the number of vehicles between the two images, fieldwork will have to be done, carrying out a manual traffic count.

On the other hand, it is also proposed a minimum threshold of expected vehicles per kilometre of road, to avoid situations where no vehicle is counted and thus stay on the side of safety. If the number of vehicles counted is less than the minimum set out in Table 6, the

Table 6 Minimum proposed vehicle occupancy according to traffic speed

v (km/h)	Minimum proposed vehicle occupancy per lane and road kilometre (number of vehicles/km)*				
	Number of lanes				
	1	2	3	4	5
50	2	4	5	7	8
60	2	3	5	6	7
70	2	3	4	5	6
80	2	3	4	5	6
90	1	2	3	4	5
100	1	2	3	4	5
110	1	2	3	4	4
120	1	2	3	3	4

*Rounded up to get integer numbers

number of vehicles calculated according to this table for the total number of lanes will be established. The minimum number proposed is 5% of the maximum number (Table 5). It is observed that for common one- and two-lane roads, this proposed percentage (5%) establishes a reasonable minimum number of vehicles, between 1 and 3, per kilometre for the different speeds.

3.3.2.2 Sensitivity However, as mentioned earlier, not all cars have the same sensitivity, as older ones have less protection for occupants. According to their age, three levels of sensitivity are proposed, as shown in Table 7. A vehicle sensitivity factor (C_{sv}) of 0.61 will be used, corresponding to the percentage of those over ten years old, to apply to the total number of vehicles exposed according to the criteria described above. Although this percentage may vary annually, no significant change is expected, and this fixed coefficient is set as a reference value regardless of the year of application of this methodology. In this way, a reduction in the number of vehicles will be obtained considering only those classified with medium and high sensitivity, assuming that the sample of analysis vehicles has the same percentages as the national vehicle fleet (population).

3.3.2.3 People exposed in old vehicles Keeping in mind that the assessment of potential damage is based on exposed people, the total number of expected occupants from the proposed number of vehicles should be estimated. To assimilate the level of potential damage between homes and vehicles, it is proposed to consider that the occupancy of vehicles is equal to the average occupancy that a dwelling can have. According to the Generalitat de Catalunya (the Catalan Government), an average of 1.95 people live in Catalan homes. This way, we can establish that two people will occupy each vehicle. Therefore, the vehicle occupancy rate is defined ($C_{ov}=2$). Based on these data, the number of occupants will be calculated as C_{ov} multiplied by the number of vehicles/km.

Thus, based on the ADT criterion and considering the coefficient of sensitivity for vehicles proposed, the expected number of persons exposed per kilometre, in cars over 9 years old (n_{pers}), can be calculated analytically from the expression (8):

$$n_{pers} = C_{sv} \cdot C_{ov} \cdot \frac{\mathrm{ADT}}{24 \cdot v} \approx \frac{\mathrm{ADT}}{19.7 \cdot v} \tag{8}$$

where C_{sv} is the coefficient of sensitivity of vehicles, C_{ov} is the coefficient of occupancy of vehicles, v is the speed limit of the flooded section expressed in kilometres per hour, and ADT is the Average Daily Traffic on the road section of the study. The same result is obtained graphically from Fig. 12.

This number of persons should be compared with the maximum and minimum number of exposed persons that can be inferred from Table 5 (maximum) and Table 6 (minimum) by means of Eq. (9). The maximum or the minimum number of persons will be set if this calculation results in a number of people above or below the proposed extreme thresholds (Table 8).

Table 7 Percentage of national vehicle fleet (DGT (2019)) and level of sensitivity of the vehicle according to its age

Vehicle age	% Of vehicles	Sensitivity
Under 9 years	39	Low
Between 10 and 14 years old	24	Medium
More than 15 years	37	High

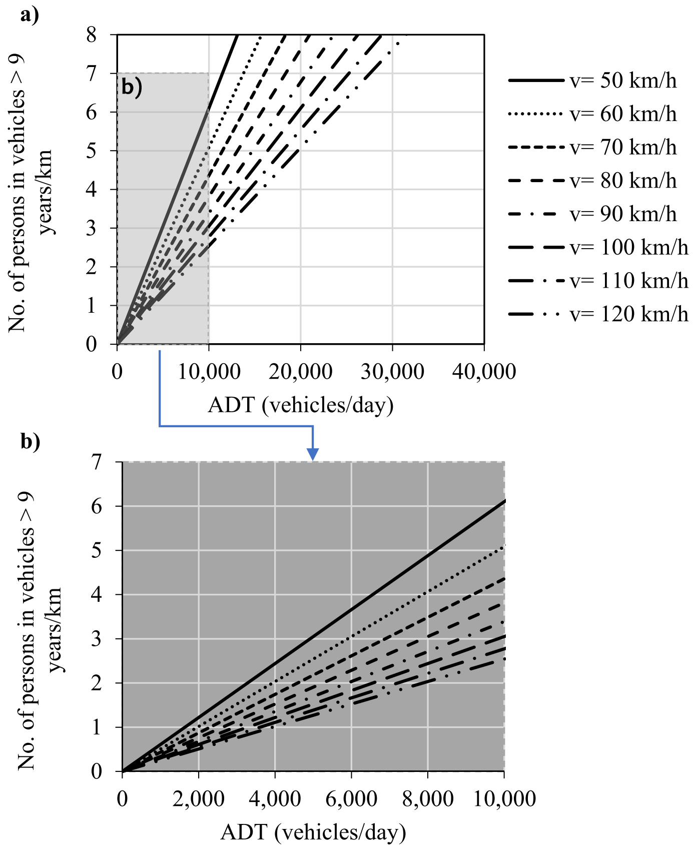


Fig. 12 Relationship between No. of expected exposed persons in vehicles over 9 years old per flooded road kilometre and ADT

For the calculation of people exposed in particular situations where the ADT criterion is unrealistic (Fig. 11), the number of people exposed in cars over 9 years old (n_{pers}) can be calculated analytically from the expression (9).

$$n_{\mathrm{pers}} = C_{\mathrm{sv}} \cdot C_{\mathrm{ov}} \cdot n_{\mathrm{vehicles}} = 1.22 \cdot n_{\mathrm{vehicles}} \tag{9}$$

where n_{vehicles} is the number of vehicles obtained from the aerial images without this number less than the minimum vehicle occupancy (Table 6).

3.3.3 Potential Damage Levels

The proposed levels of damage in case of a potential flood of one or more roads will be based on the proposal of the Technical Guide (1996 and 2021) when it comes to potential damage to human lives (Population at risk) (Table 1). However, it has been considered the expected number of occupants per dwellings affected by the high-hazard flood instead of only the number of dwellings. As mentioned in the section defining the vulnerability criterion, it has been proposed that the number of people expected on average in each household is the same as that found in a vehicle.

Table 8 No. of persons exposed to the maximum and minimum proposed number of vehicles, in those older than 9 years

v (km/h)	Maximum number of people exposed per km in vehicles over 9 years old					Minimum number of people exposed per km in vehicles over 9 years old				
	No. of lanes					No. of lanes				
	1	2	3	4	5	1	2	3	4	5
50	40	79	118	157	196	3	5	7	9	10
60	33	66	99	132	165	3	4	7	8	9
70	30	59	88	118	147	3	4	5	7	8
80	26	52	77	103	129	3	4	5	7	8
90	24	47	70	93	116	2	3	4	5	7
100	21	42	63	83	104	2	3	4	5	7
110	20	40	59	79	98	2	3	4	5	5
120	19	37	55	74	92	2	3	4	4	5

*Rounded up to obtain integers from formula (9), and considering as n_{vehicles} the data in Table 5 (maximum vehicle occupancy) and Table 6 (minimum vehicle occupancy)

Thus, three levels of potential damage (low, medium, and high) are proposed (Table 9) and the corresponding classification of the dam/pond. These potential damage levels are only established for the flooded area with a high hazard level according to the hazard criteria defined in Fig. 8.

The invented example in Fig. 13 shows a section of flooded road (N-141c) near Calders (a municipality in Catalonia). Red indicates the high-hazard zone (Fig. 8), which affects 700 m of road. According to the latest data of the Generalitat de Catalunya, the ADT for this section is 14,000 vehicles per day. This section has a speed limit of 50 km/h.

With these data, the calculation of potentially exposed people would be as follows:

$$n_{\text{pers}} = \frac{ADT}{19.7 \cdot v} \cdot 0.7 = \frac{14,000}{19.7 \cdot 50} \cdot 0.7 = 9.9\text{persons}$$

Therefore, the level of potential damage would be established as medium, leading to a B dam/pond classification ($2 \leq$ people ≤ 10). If the aerial photography observation criterion had been considered for exceptional cases where the ADT criterion is not valid, 5 vehicles would have been identified, and, according to the expression (9), 6.1 people could suffer damage. This number of people is higher than the minimum 3.5 per 0.7 km of flooded road (5 people/km), according to Table 8 (v = 50 km/h and 2 lanes). The dam/pond, then, would

Table 9 Dam classification proposed according to the potential damage to human lives on roads

Type of potential damage	Low damage	Medium damage	High damage
Potential damage to human lives (Population at risk) (No. Cars)	<1 car	1≤ cars ≤5	cars >5
Potential damage to human lives (Population at risk) (No. Persons)	<2 persons	2≤ persons ≤10	persons >10
Classification of the dam	C	B	A

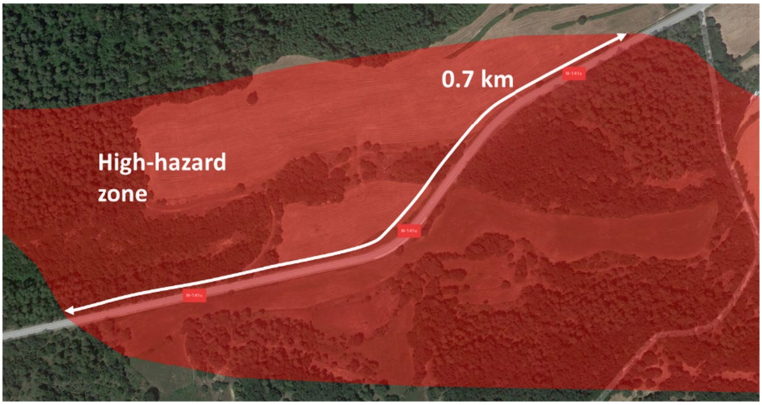


Fig. 13 Example of a 2-lane road flood (*Source*: Google Earth)

also be classified as B by counting vehicles in the aerial image. The maximum threshold would be 79 people/km (Table 8), therefore 55.3 people in 0.7 km. It is thus verified that the numbers of people obtained with the criteria of the ADT (9.9 people) and of the observation of the aerial image (6.1 people) are included between the maximum threshold (55.3 people) and the minimum (3.5 people).

4 Application to three existing ponds in Catalonia

This section presents the application of the new methodology proposed and described in the previous section to three (3) specific real cases chosen by the Catalan Water Agency (ACA for its acronym in Catalan). The flood scenario resulting from a pond failure in dry weather and with the reservoir at its maximum normal level of operation has been considered.

The classification of the pond (A, B, C) according to the new methodology is compared with the classification that would result from applying the criterion currently proposed in the Technical Standard approved by Royal Decree 264/2021 and in the Technical Guide (1996 and 2021), with the clarifications defined in the "Criteria for the interpretation of the Technical Guide for the Classification of Dams according to the potential risk" (Agencia Catalana de l'Aigua (ACA) 2014).

The starting point for this study was the original three (3) ponds classification projects. These ponds were chosen because they potentially affected roads; however, their proposed classification was the most restrictive of the various potential impacts for a possible flood, not only roadways. Therefore, although the types of potential damage resulting from a possible flood caused by the rupture or malfunction of these ponds are different, the present study considers roads the only analysis element. In this way, the pond classification will only concern the impact of roads.

The results files of the hydrodynamic models were not available, only the flood map presented with the pond classification project. Therefore, the hazard map could not be drawn up, and the entire length of the flooded road was considered of high hazard. Therefore, the results obtained here will be conservative. Considering only the high-hazard flood extent could make the classification the same or lower, but never higher.

The first pond analysed (Pond #1) is located outside the Public Hydraulic Domain and has two possible flood pathways: North (stream in Les Planes) and East (stream in La Plana del Fuster and Barranc de Mont-redon) (Fig. 14). It is in the Ebro River basin, in the municipality of Rasquera (Tarragona), and is a pond of loose materials with a waterproof sheet of high-density polyethylene (HDPE) of 2 mm on geotextile of 285 gr/m^2. According to the classification proposal project carried out by its owner, its classification is C.

The second pond chosen (Pond #2) is in Bellaguarda (Lleida) municipality on the Vall dels Horts riverbed, which corresponds to the Ebro River basin. It has a single flood pathway (Fig. 14). It is a pond of loose material with a waterproof sheet of high-density polyethylene (HDPE). According to the classification proposal project carried out by its owner, its classification is C.

The third pond under study (Pond #3) is in the municipality of La Pobla de Massaluca (Tarragona), and its function is to store and regulate water from the Ebro at the mouth of the Matarraña River. There are two possible flood pathways (Fig. 14) along which the flood wave would travel in case the pond breaks. In a north-westerly direction, the first follows the Barranc del Moro (La Pobla de Massaluca), and the second in a north-easterly direction follows the Barranc de Voravall. Only the second flood pathway intersects with infrastructures that can be damaged. According to the classification proposal project carried out by its owner, its classification is C.

The delimitation of the road section that may be affected by the flood wave in each case is provided in Fig. 14. The different roadways have been identified, as well as the depth and velocity data that the classification proposal projects indicate can be given to each of the roads.

It is verified that high hazard would occur in all cases, according to the criteria defined in Fig. 8 and as shown in Table 10. In this same table, the number of lanes, speed limit, and ADT of each of the roads that could be affected is presented and the length affected by the flood. These data are necessary to be able to apply the methodology proposed above.

From these data, the maximum and minimum limits of persons who could be harmed (in old cars) can be obtained according to the values in Table 8. The ADT criterion can also be applied from equation [8]. The results are presented in Table 11 together with the proposed pond classification according to the level of potential damage defined in Table 9.

5 Discussion

The three ponds would be classified as C according to the application of the proposed methodology, although it has been assumed that the entire flood was of high hazard. Thus, even if part of the road were flooded with medium or low hazard, their classification would continue to be C. With the application of this methodology, it has been observed that one of the most relevant variables when classifying the pond (or dam) will be the potentially floodable road length. The number of persons potentially exposed to the flood estimated from this methodology corresponds to each kilometre of a flooded road; however, the cases studied are far from presenting one flooded kilometre. In this sense, the exercise of evaluating the classification of these three ponds according to the length of the flooded road has been carried out to be discussed. Figure 15 shows this relationship for the three roads studied.

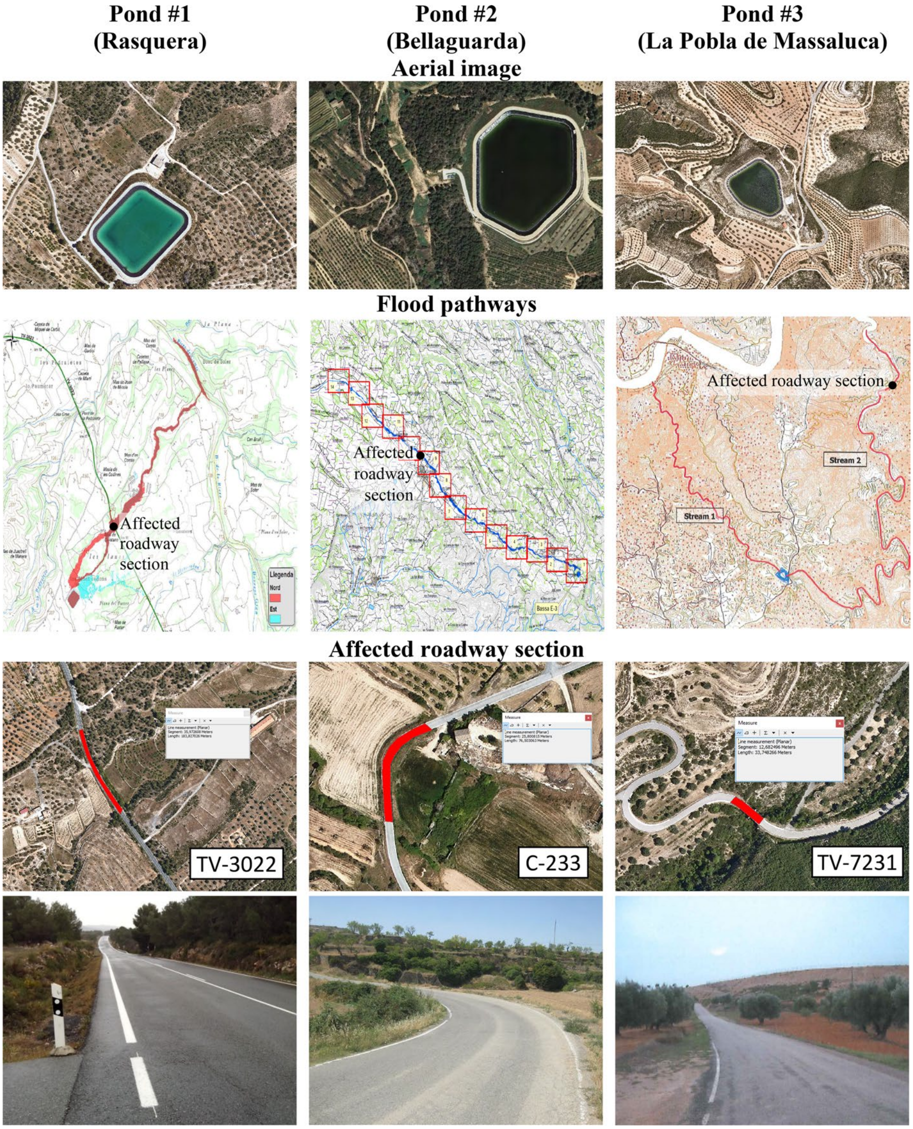


Fig. 14 Selected ponds and the roads potentially affected by a flood (Source: Google Earth)

Both the TV-3022 (Pond #1) and the C-233 (Pond #2) require 665 m of the flooded road for the pond to be classified as B and 3,335 m to be classified as A. The minimum threshold of exposed vehicles has been fixed in these two cases as these roads do not have an ADT high enough to exceed the minimum threshold. For example, an ADT of 6,000 vehicles/day on TV-3022 would cause the number of people exposed to exceed the minimum threshold.

On the other hand, the TV-7231 should have been flooded at a length of 1,000 m so that the Pond #3 would have been classified as B and 5,000 m to be classified as A.

Table 10 Data from roads that could be affected by the flood wave

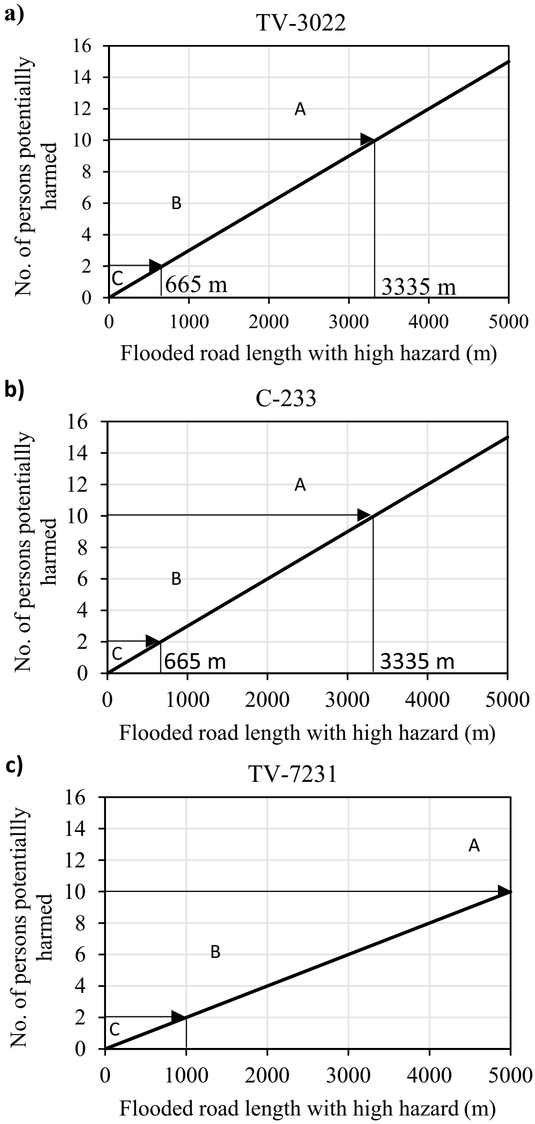
Pond #	Municipality	Road	Flood hazard variables	Length (m)	No. Lanes	v (km/h)	ADT (veh/day)
1	Rasquera (Tarragona)	TV-3022	Depth (y): 0.41 m Velocity (v): 1.88 m/s $v \cdot y = 0.78\ m^2/s$	184	2	90	1407.00
2	Bellaguarda (Lleida)	C-233	Depth (y): 0.92 m Velocity (v): 0.8 m/s $v \cdot y = 0.74\ m^2/s$	76	2	90	281.00
3	La Pobla de Massaluca (Tarragona)	TV-7231	Depth (y): 0.88 m Velocity (v): 10 m/s $v \cdot y = 8.8\ m^2/s$	34	1	90	501.00

Table 11 Classification of the selected ponds according to the potential damage to human lives on roads

Pond #	Municipality	Road	*n_{pers} (max)	*n_{pers} (min)	*n_{pers} (ADT)	*n_{pers}	Damage level	Class.
1	Rasquera (Tarragona)	TV-3022	8.65	0.55	0.15	0.55	Low	C
2	Bellaguarda (Lleida)	C-233	3.57	0.23	0.01	0.23	Low	C
3	La Pobla de Massaluca (Tarragona)	TV-7231	0.82	0.07	0.01	0.07	Low	C

* n_{pers}: number of persons who might be harmed

Fig. 15 Relationship of the number of persons who could be harmed depending on the length of the road flooded with high hazard



The slope of the functions shown in Fig. 15 indicates how relevant the flooded road's length is. The higher the ADT, the lower the straight-line slope; in other words, the less flooded road length will be required to be classified as B or A.

6 Conclusions

In this study, a methodology has been proposed to assess the impact on roads due to flooding that could occur in the event of a dam or pond failure and to be able to classify it based on this assessment. This methodology is based on assessing the potential damage, considering some proposed hazard and vulnerability criteria. The first is based on vehicle stability, using experimental studies as a reference. Vulnerability is considered by the sensitivity of older cars, which protect occupants four times less than new ones. As part of vulnerability, exposure is the most complex aspect when it comes to moving elements, such as cars. In this sense, a criterion is established based on the Average Daily Traffic (ADT) of roads and setting a maximum and a minimum number of vehicles expected in the area receiving the flood.

The appropriateness of the proposed methodology is verified from the results obtained after being applied to three ponds, which were already classified as C considering all the elements that can be damaged according to the instructions of the Technical Guide (1996 and 2021) not just roads. With this proposed new methodology, the impact on a road can mean the classification as B or A of a dam or pond if its ADT and/or the road high hazard flooded length is large enough. One of the most important aspects of this novel approach is the change of paradigm that represents. Instead of paying attention on economic flood damage, the procedure presented here to estimate potential flood damage to roads is entirely based on the safety of people. The proposed methodology strikes an appropriate balance between scientific rigour and simplicity of application. Additionally, this methodology, apart from its application in dams' classification, can be employed within the decision-making process in flood risk management.

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Declarations

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